Journal of Cleaner Production 103 (2015) 469–482

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

The impact of climate targets on future steel production – an analysis based on a global energy system model☆

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ARTICLE INFO

Article history:
Received 27 August 2013
Received in revised form
10 March 2014
Accepted 20 April 2014
Available online 30 April 2014

Keywords:
ETSAP-TIAM
SAAM
Steel production
Technology choice
Climate change

ABSTRACT

This paper addresses how a global climate target may influence iron and steel production technology deployment and scrap use. A global energy system model, ETSAP-TIAM, was used and a Scrap Availability Assessment Model (SAAM) was developed to analyse the relation between steel demand, recycling and the availability of scrap and their implications for steel production technology choices. Steel production using recycled materials has a continuous growth and is likely to be a major route for steel production in the long run. However, as the global average of in-use steel stock increases up to the current average stock of the industrialised economies, global steel demand keeps growing and stagnates only after 2050. Due to high steel demand levels and scarcity of scrap, more than 50% of the steel production in 2050 will still have to come from virgin materials. Hydrogen-based steel production could become a major technology option for production from virgin materials, particularly in a scenario where Carbon Capture and Storage (CCS) is not available. Imposing a binding climate target will shift the crude steel price to approximately 500 USD per tonne in the year 2050, provided that CCS is available. However, the increased prices are induced by CO_2 prices rather than inflated production costs. It is concluded that a global climate target is not likely to influence the use of scrap, whereas it shall have an impact on the price of scrap. Finally, the results indicate that energy efficiency improvements of current processes will only be sufficient to meet the climate target in combination with CCS. New innovative techniques with lower climate impact will be vital for mitigating climate change.

1. Introduction

Iron and steel production is one of the major sources of anthropogenic CO_2 emissions. In the EU, the sector is responsible for 4.7% of the total emissions, which amounts to a total of 182 million tonnes of CO_2 (UNFCCC, 2012). The climate change externality has recently been included in the cost structure of products produced within the EU through the EU Emission Trading System (EU ETS). This has led to discussions between industry organisations and policy-makers whether the EU climate policy is negatively affecting the competitiveness of European industries or not (Gielen and Moriguchi, 2003, 2002a, 2002b; Okereke and McDaniels, 2012).

Furthermore, ETS schemes have recently been established in several regions of the world, such as Australia, the EU, Kazakhstan, New Zealand and Switzerland as well as in Québec in Canada and California, Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont in the United States. Several other countries are considering implementation of an ETS and others have already scheduled implementation (International Carbon Action Partnership, 2013). There is already an agreement aimed at linking the EU ETS and the Australian ETS, which is a step towards an international CO_2 price (European Commission, 2013).

This paper addresses the influence that global climate targets may have on future technology choices for iron and steel production, particularly highlighting steel demand patterns and scrap availability. The global climate targets required for mitigating climate change are represented by a binding target limiting radiative forcing in the model, which corresponds to stabilization of the global mean temperature increase between 2.4 and 3.2 °C (Barker

☆ The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission.

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http://dx.doi.org/10.1016/j.jclepro.2014.04.045

et al., 2007). The global energy system model ETSAP-TIAM was enhanced with explicit iron and steel production technology detail. The model was used to find cost-efficient technology pathways under radiative forcing constraints. In addition, ETSAP-TIAM was coupled with SAAM, a model developed to assess the global availability of scrap. This approach takes the iron ore resources and scrap availability into account, which enables discussions on accumulation of in-use steel in society and implications for future technology choices. Scenarios highlight the impact of future steel demand patterns, a binding global climate target, and no future CCS availability. Essentially, the study addresses the question: *how may a binding global climate target influence future iron and steel technology deployment and scrap use?*

The next section presents the methodology of the paper, including the current and future technology trends in the iron and steel sector. Model results are presented and discussed in the subsequent sections. The main conclusions drawn from the study are then presented, including a discussion on the policy implications of the results. Details on the steel technology deployment are given in Appendix A and details on the new steel technology representation in ETSAP-TIAM are given in Appendix B.

2. Methodology

Traditionally, iron and steel production has been divided into two production routes. The primary route uses iron ore as ferrous resource. These technologies are characterized by high energy demand per tonne of steel produced (see Table 1). Reduction of iron ore to iron, which is done in a blast furnace (BF), requires large amounts of coal as reduction agent. Together with the high temperatures required, it results in the high energy demand of the process. The iron is then refined into steel in a basic oxygen furnace (BOF) or the more energy intensive open hearth furnace (OHF), which is only used to small extent today. Some of the primary production technologies use a limited amount of scrap to supplement the iron ore. There are also some direct reduction (DR) technologies in use, also referred to as solid state reduction, in which iron ore is reduced to steel or other iron products directly. Traditional primary production technologies result in high CO_2 emissions (see Table 1), but research and development in the sector aims at reducing emissions by optimizing current processes and developing innovative approaches (Silveira et al., 2012).

The secondary production route uses steel scrap as ferrous resource and is less energy intensive than the primary route. Scrap is refined into steel using an electric arc furnace (EAF). Steel production based on scrap is less energy intensive since the scrap resource has already gone through the reduction process during its previous life cycle (see Table 1). The secondary route could theoretically be close to CO_2 emission free using current technology since it uses electricity as its main source of energy (see the lower boundary of the Scrap/EAF route in Table 1) (Silveira et al., 2012).

Table 1
Energy and CO_2 emission intensities of steel production processes (International Energy Agency, 2007; World Steel Association, 2008). The range in energy demand depends on the technology used and the aimed steel product (World Steel Association, 2008). The specific CO_2 emissions are country averages for the various routes and the ranges account for the difference in CO_2 emissions for CO_2-free versus coal-based electricity generation (International Energy Agency, 2007).

Processes	Specific energy consumption [GJ/tonne steel]	Specfic CO_2 emissions [tonne CO_2/tonne steel]
Primary Route – BF/BOF	19.8–31.2	
- Advanced BF		1.3–1.6
- Present Average BF		1.5–1.8
Primary Route – BF/OHF	26.4–41.6	
Primary Route – DR/EAF	28.3–30.9	
- Coal-based		2.3–3.0
- Natural Gas-based		0.7–1.2
Secondary Route – Scrap/EAF	9.1–12.5	0.3–0.5

Between the late 1990s and 2012, total steel scrap use increased approximately 60%, from 350 million tonnes to more than 550 million tonnes. Crude steel production increased by 90% in the same period (Bureau of International Recycling, 2013, 2010; International Iron and Steel Institute, 2000). Despite the relatively slow growth of scrap-based steel in the past decades, the structural shift towards increased share of secondary production of steel offers a plausible pathway for reducing the CO_2 emissions from steel production in the long run. However, as shown in previous studies, scrap availability is limited by the historic production and the time lag of its use in society (Davis et al., 2007; Grosse, 2010; Müller et al., 2011, 2006; Pauliuk et al., 2013). Grosse (2010) shows that recycling is not enough to meet the future demand for steel products at the current growth rate of consumption, concluding that policies for increasing sustainable development cannot solely rely on recycling.

In addition to recycling, other solutions exist to reduce the CO_2 emissions from steel production, including new and innovative processes for primary production of steel. The European Ultra-Low CO_2 Steel making (ULCOS) initiative aims at reducing CO_2 emissions from steel production technologies by 50% compared to current best practice. Three groups of options, at different stages of development, are considered within this initiative: (i) carbon capture and storage (CCS) embedded in current steel production technologies; (ii) decarbonised steel production using hydrogen or electrolysis in the reduction process (e.g. the MIDREX process can use synthetic gas containing approx. 70% pure hydrogen as reduction agent), and (iii) use of biomass as reduction agent (potentially together with CCS). These processes have high potential to reduce emissions, but their implementation will require significant investments, which are not foreseen in the short-term (Gojić and Kožuh, 2006; Birat, 2009; Birat et al., 2008; Elliot and Kopfle, 2009). In fact, the technologies proposed will most likely require political incentives to become economically viable. Moya and Pardo (2013) confirm this by showing that major CO_2 emission reductions in the steel industry would only be viable with long payback periods. Climate policy could introduce a cost for CO_2 emissions and potentially influence the cost-efficiency of certain technologies.

Several top-down studies have used regression analysis and econometric models to analyse future trends in the steel sector. Yellishetty et al. (2010) used regression analysis based on previous trends to predict the future production of steel using current technology options. Also the future energy intensity of production was estimated using regression. Lutz et al. (2005) enhance the econometric and environmental model Panta Rhei adding details on steel production technology to analyse future technology change in the German steel industry. Schumacher and Sands (2007) identify the lack of technology detail in computable general equilibrium (CGE) models, which are commonly used for macroeconomic analyses, and enhance the approach with cost-functions to represent the two main production routes. Boyd and Karlson (1993) show a correlation between past technology choice trends in United States' steel industry and energy prices, also using regression analysis. However, the approaches used in the studies mentioned are limited to simulating the current production routes and do not capture innovation in the form of new technologies that can substitute these processes. Furthermore, regression analysis only forecasts the future based on past trends rather than optimizing production to meet a specific objective.

A recent bottom-up study by Pardo and Moya (2013) provides an extensive review of the current best-practice and innovative technologies for steel production in the EU, resulting from cost-benefit analyses for future technology choices. The model is based on exogenous variables, i.e. steel consumption, steel production and scrap availability as well as resource, electricity and CO_2 prices. Scenarios show that the major technologies for reducing CO_2 emissions would be top gas recycling in blast furnace and CCS combined with an on-site power plant. Significant increase in CO_2 prices makes top gas recycling combined with CCS for the blast furnace cost effective. Increasing energy and raw material prices would make direct reduction technologies based on natural gas cost effective.

As part of the ULCOS initiative, Bellevrat and Menanteau (2009) investigated technology choice for global steel production under different climate policy scenarios. The model used, POLES, a partial equilibrium model of the global energy system, which was coupled with ISIM, a steel-sector simulation model including explicit steel production technology representation (Bellevrat and Menanteau, 2009; Hidalgo et al., 2005, 2003). Future technology choice for steel production has also been previously analysed using STEAP, a partial equilibrium model focused on the iron and steel sector in eleven world regions. The studies highlight the case of Japan and show that carbon leakage could be extensive if only Europe and Japan introduce a CO_2 tax (Gielen and Moriguchi, 2003, 2002a, 2002b).

In the approach used by Bellevrat and Menanteau (2009), POLES/ISIM assumes an inverse U-shaped relationship between steel consumption per GDP and GDP per capita. Pauliuk et al. (2012) mean that this approach is very sensitive to the GDP growth rate. They also note that there is no assessment of scrap availability in POLES and, hence, the technology choice between the primary and secondary route is made on an economic basis only, neglecting the availability of the raw material. To bridge these gaps, the *Scrap Availability Assessment Model* (SAAM) was developed to capture the scrap availability based on the future demand scenarios and historic steel consumption. SAAM also gives indications on the in-use steel stock as well as the saturation levels at the global scale, providing important insight on future demand patterns of steel products. The concept of in-use steel stock is based on the fact that steel is accumulated in society over time (residence time) as part of infrastructure, machinery, vehicles and other everyday products. When it reaches its end-of-life phase, the steel is either dumped in a landfill, becoming part of the obsolete stock (steel that out-served its purpose, but cannot be recovered), or used as scrap feedstock in the secondary production route. SAAM was developed within the scope of a KIC InnoEnergy initiative, the Energy Systems Analysis Agency (ESA[2]) (Morfeldt et al., 2013).

SAAM was integrated with *ETSAP-TIMES Integrated Assessment Model* (ETSAP-TIAM), a well-established global energy model maintained by *Energy Technology Systems Analysis Program* (ETSAP), to model future technology choices for the iron and steel sector. Although the model characteristics are similar in ETSAP-TIAM and POLES/ISIM, the steel production technologies are represented in higher level of detail in ETSAP-TIAM, including production and use of siderurgical gases (i.e. gases produced as by-products from steel production processes). ETSAP-TIAM also benefits from cost-optimisation, which means being able to choose the most cost-efficient technology pathway for a specific region under a given set of constraints, whereas POLES/ISIM simulates the development of a scenario based on a given set of rules. Another benefit of using ETSAP-TIAM is its well-developed climate module, which translates targets on radiative forcing into limitations on emissions of the greenhouse gases (CO_2, CH_4 and NO_x). The target on radiative forcing is directly related to the global mean temperature increase (Barker et al., 2007).

2.1. SAAM: Global scrap model

SAAM estimates the scrap availability annually, based on estimated steel demand from 1900 to 2005 and projected steel demand from 2005 to 2150 (e.g. based on the ETSAP-TIAM demand scenarios). Historic demand was assumed to increase exponentially with an annual growth rate of 3.5%, following Grosse's (2010) approximation for 1950–2007, and based on the 2005 value of each scenario. To harmonize the data with ETSAP-TIAM, the results are given for every five years of the modelled period. SAAM is based on the following equation for estimating the scrap made available at a certain point in time:

$$S_t = \sum_{i=0}^{n} \eta_i \cdot \rho_i \cdot (1 - \gamma_i) \cdot P_i, \quad (1)$$

where S_t is the scrap made available during the time period t; η_i is the share of steel use that each product group, i, has in the total in-use steel stock; ρ_i is the recycling rate; γ_i is the fraction of the in-use steel forming obsolete stocks; and P_i is the total steel produced for the time period equal to t minus the average life-time, T, of the product group i (see graphical representation in Fig. 1).

The parameters were chosen based on estimations provided by Pauliuk et al. (2013) and are shown in Table 2. The average sectoral split (calculated based on the input to the model developed by Pauliuk et al. (2013)) was used as the global average. The base value for the average life-time of the model developed by Pauliuk et al. (2013), previously estimated by Müller et al. (2011), were used as the global average life-times for the product groups. The fraction of in-use steel forming obsolete stocks was assumed to be steel used in, for example, construction that would not be recovered when the structure is demolished. This type of steel scrap was estimated at 10% of the total steel produced (Pauliuk et al., 2013).

The recycling rates, ρ_i, were assumed to gradually increase over the whole time period, in contrast to Pauliuk et al. (2013) who kept the rates constant. Recycling rates were assumed to grow exponentially by 1% annually during the period 1900–2005. Capturing technological improvements, the rates continue growing exponentially after 2005 at paces designed to reach 100% recycling in the year 2100. After 2100, the recycling rates were assumed to be equal to 100%. While the recycling rates approached 100%, the share of obsolete stock remained constant at 10% for all years. Hence, the effective scrap made available never exceeded 90% of the steel produced.

The product category *New scrap* was the scrap from product manufacturing that never enters society. Hence, it can be recycled

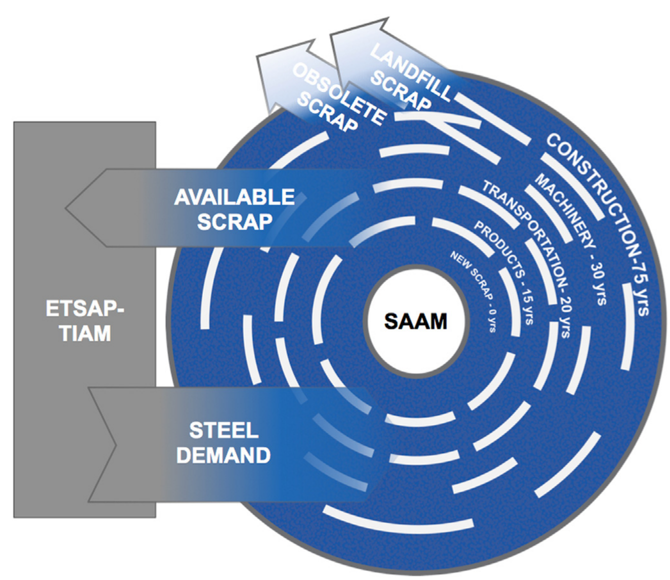

Fig. 1. Graphical representation of SAAM and the link with ETSAP-TIAM.

Table 2
Input parameters for SAAM.

Product group	*T*	η_i	ρ_i (for 2005)
New scrap	0 years	9%	100%
Products	15 years	5%	58%
Transportation	20 years	40%	82%
Machinery	30 years	15%	87%
Construction	75 years	40%	82%

as it arises (in the same year it is produced). *Own scrap*, which is sometimes called home scrap, was not modelled, since it is recycled within the factory gates and, therefore, is included in the total output of production.

2.2. ETSAP-TIAM: global energy system model

ETSAP-TIAM is a partial equilibrium model, optimizing the cost of the global energy system based on detailed technology representation for production, transmission and distribution of energy carriers. The model comprises several thousands of technologies throughout all sectors of the economy. ETSAP-TIAM also includes emission coefficients for three major greenhouse gases: CO_2, CH_4 and N_2O. ETSAP-TIAM was first formalized by Loulou (2007) and Loulou and Labriet (2007a) and represents the global energy system with the individual modelling of 15 global regions (see Appendix A).

One of the most important parameters for technology deployment in ETSAP-TIAM is the demand for each time period. The sectoral demands of each region in ETSAP-TIAM are based on exogenous drivers provided by the CGE-model GEMINI-E3. The sectoral demands induce an energy service demand through the energy intensity of a given sector (Loulou and Labriet, 2007b). For iron and steel production, the technology representation was enhanced by adding explicit representation of iron and steel producing technologies, based on Van Wortswinkel and Nijs (2010), Piessens et al. (2009), and discussions with industry experts (see complete database of steel production technologies in Appendix B). Trade of iron and steel is not modelled in the current version of ETSAP-TIAM and a fixed price was assumed for the mining of iron ore of 80 USD per tonne of lump iron ore. A fixed price of 50 USD per tonne was also assumed for recycling of scrap. However, the price of scrap was inflated by an additional scarcity value (see explanation in Section 4.2).

2.3. Scenario definition and assumptions

The models assume a uniform final steel product, in line with previous studies (Hidalgo et al., 2005; Bellevrat and Menanteau, 2009). Although currently scrap-based steel production cannot fully substitute steel produced from virgin materials in terms of quality requirements, it was assumed that research will make this possible in the future. Already today, the quality of steel produced in the secondary route can be improved by mixing it with direct reduced steel (Hidalgo et al., 2003; Worrell et al., 1997). In-use iron stock is assumed to be equal to in-use steel stock throughout this study. The reason for this assumption is that ETSAP-TIAM only considers the demand for steel, not for iron products. The material losses when refining iron to steel are considered as *own scrap* and will therefore be fed back into the process. In ETSAP-TIAM, the CO_2-price as well as scrap and raw material prices for steel production are assumed to be uniform across regions.

Based on insight provided by SAAM on the saturation of in-use steel stock, two demand scenarios were analysed (see matrix in Table 3). In the scenario *Demand stagnation in 2100* (used in the current version of ETSAP-TIAM), demand is assumed to be growing at a rate of 4.2% annually in 2005, gradually decreasing to 0% in

Table 3
Scenario definition.

Climate ambition	*Demand stagnation in 2100*	*Demand stagnation in 2050*
Reference scenario	The reference scenario does not envisage any ambitious climate targets. Radiative forcing in 2100 is 6.7 W/m^2 and CO_2 concentration more than 600 ppm.	
3.5 RF Climate	The climate module of ETSAP-TIAM is used for these scenarios to limit the radiative forcing up to a level of 3.5 W/m^2 in any timeframe.	
3.5 RF Climate (no CCS)	This scenario is similar to the previous, except that CO_2 storage is not allowed in any sector of the global economy.	

2100. In addition, another scenario was created, *Demand stagnation in 2050*, to align saturation levels of in-use steel stock of the demands with previous research indicating saturation levels of industrialized economies (see the discussion in Section 3 for details). In *Demand stagnation in 2050*, demand is assumed to be growing at a rate of 3.5% annually in 2005, linearly decreasing from 3.5% to 0% in the year 2050.

The regional division of the *Demand stagnation in 2050* scenario in ETSAP-TIAM was developed based on the assumption that demand in developing regions, such as Africa, China, India, Central and South America and Developing Asia, will increase in the short-term to then stabilize and, in some cases, decrease in the long-term (see Fig. 2). This assumption is supported by available literature (Grosse, 2010; Holloway et al., 2010; Müller et al., 2011; Pauliuk et al., 2013). The regional demands were built empirically to meet two objectives: (i) a common level of approximately 300 kg steel demand per capita in 2100 in all regions, and (ii) global demand stagnation in 2050, resulting in a constant level of global steel demand in the following years up until 2100.

The global climate targets were simulated by the radiative forcing constraint of 3.5 W/m^2 in any timeframe. Radiative forcing is the combined effect of the greenhouse gases warming up the planet. Using radiative forcing as the target instead of the concentration of CO_2 in the atmosphere has the benefit of taking other greenhouse gases into account as well. According to the Intergovernmental Panel on Climate Change, a radiative forcing of 3.5 W/m^2 will result in an approximate global mean temperature increase between 2.4 °C and 3.2 °C above pre-industrial levels. In any case, since climate sensitivity introduces an uncertainty in this estimation, radiative forcing is a more reliable target than a certain level of global mean temperature increase. In terms of CO_2, the binding climate target scenario considered in this paper is close to a concentration of 450 ppmv of CO_2 only or 550 ppmv CO_2 equivalents in the atmosphere when including all long-lived greenhouse gases. It should be noted that the reference scenario used in this paper results in an unbound radiative forcing of

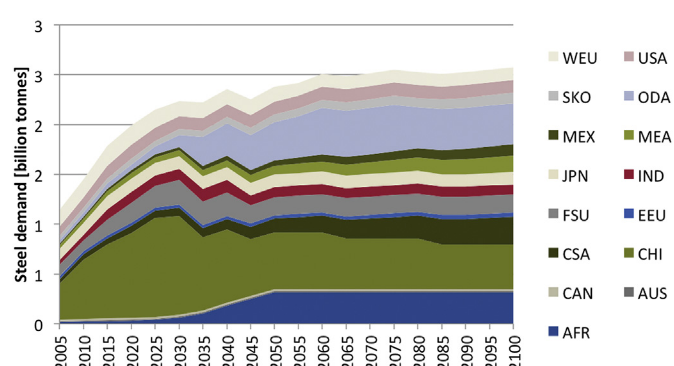

Fig. 2. Regional division of steel demand for *Demand stagnation in 2050* (see Appendix A for explanation of abbreviated regions).

6.7 W/m^2 in 2100. This level of radiative forcing would yield an approximate global mean temperature increase of between 4.9 °C and 6.1 °C, levels that threaten life on Earth as we know it (Barker et al., 2007).

Previous research has shown that CCS is an important technology option for decarbonising the iron and steel industry (Bellevrat and Menanteau, 2009; Hu et al., 2006; Pardo and Moya, 2013). Also industry representatives consider CCS the decarbonisation technology closest to commercialization (European Commission, 2010). However, the plans for building the first demonstration facility using CCS connected to iron and steel were recently cancelled. As a result, no initiative for demonstration of the CCS technology in the iron and steel sector is active at the moment (EurActiv, 2012). Because of these recent developments, a technology-restricting scenario was added. This scenario has the same climate ambition, but does not allow CO_2 storage in any sector of the global economy.

3. Insights to scrap availability and in-use steel stock (SAAM)

SAAM was first run stand-alone using different demand projections to understand the implications of scrap availability on production from virgin materials. The results of this analysis are discussed in Section 3.1. The steel demand scenario currently used in ETSAP-TIAM, *Demand stagnation in 2100*, was tested in SAAM to assess the results for in-use steel stock. The results of this analysis are discussed in Section 3.2 and serve as the basis for the second demand scenario, *Demand stagnation in 2050*.

3.1. Long-term requirement for steel production from virgin materials

A dynamic analysis of the influence of demand growth on scrap availability showed future dependence on steel production from virgin materials in 2050 as well as in 2100. In other words, steel production from virgin materials will still be required even with significant reduction in short-term as well as long-term growth of steel demand compared with current trends.

The analysis, performed in SAAM, assumed that all scrap made available each year would be fully used in steel production. Even for the case when demand growth was assumed to approach zero in the short-term (i.e. the year 2015 in the model), almost 40% of the total demand would need to be met by steel production from virgin materials in 2050 (the blue line in Fig. 3a). Interestingly, reducing the long-term demand growth only fractionally reduces the requirement of steel production from virgin materials in 2050 (in Fig. 3a long-term demand growth was varied between −2.5% and 2.5%).

The long-term demand growth has a more significant influence on steel production from virgin materials in 2100 (Fig. 3b). A negative requirement for steel production from virgin materials was actually visible for the case of reducing short-term growth to between 0% and 1% combined with a negative long-term growth (the blue and grey curves crossing the *x*-axis in Fig. 3b). In this case, the negative requirement for steel production from virgin materials indicates that society would supply steel production with recycled material to the degree of being self-sufficient without the need for virgin materials. This confirms the conclusion of Grosse (2010), that a demand growth rate lower than 1% is required for recycling to make a difference in the conservation of the iron resource.

However, reducing global demand growth drastically in the short-term and aiming for negative growth in the long-term (i.e. for 2100 and beyond) is not plausible considering the future requirement of steel products in developing regions (Pauliuk et al., 2013). This means that even if we drastically reduce the growth of steel demand in the short-term, there would still be a significant requirement for steel production from virgin materials in 2050. Unless we aim at negative demand growth in the long-term, there will still be a requirement for steel production from virgin materials, even by 2100.

3.2. Saturation of in-use steel stock

SAAM was used to assess the in-use steel stock for the two scenarios, *Demand stagnation in 2100* and *Demand stagnation in 2050*. The large difference between the two scenarios, as showed by the results, is due to the high demand growth rates assumed for *Demand stagnation in 2100*. High demand growth can be expected due to the assumed coupling with the high economic growth in developing regions.

The iron resource has been estimated to approximately 230 billion tonnes (in terms of iron rather than iron ore, meaning that the amount of crude steel that could be produced is approximately the same). However, not all of this is currently available for extraction in an economically viable way using current technology. Only approximately 80 billion tonnes of iron could be economically extracted (the iron reserve). On top of this, approximately 18 billion tonnes of iron has been accumulated in society, i.e. the in-use iron stock (Müller et al., 2011; U.S. Geological Survey, 2012a, 2012b; Vital and Pinto, 2009).

As the results showed, the demand growth of *Demand stagnation in 2100* would result in a total cumulative in-use steel stock slightly above 200 billion tonnes. This number is close to the full resource potential and would require new techniques to extract iron from the Earth's crust (see Fig. 4a). This is in line with Grosse

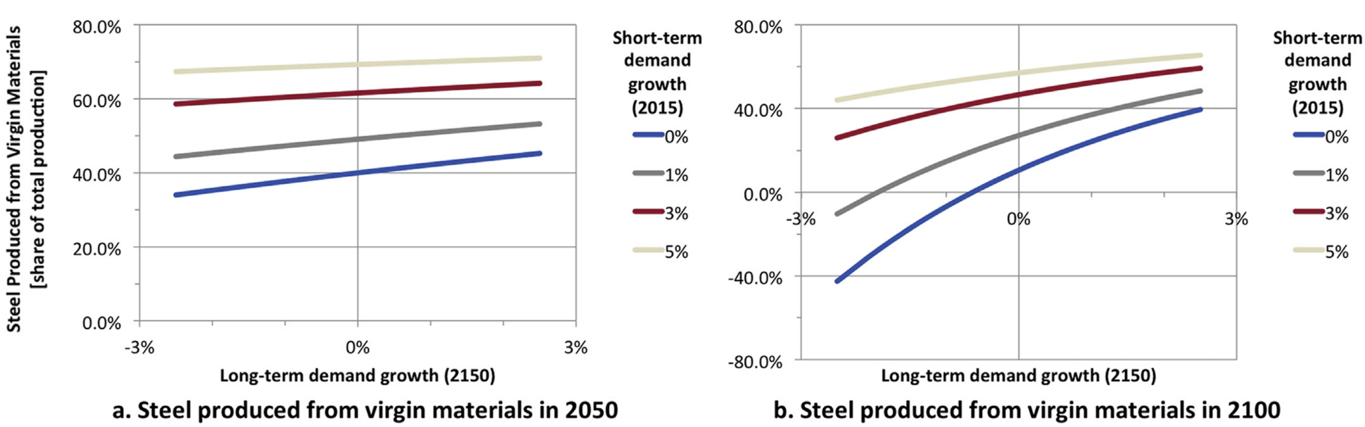

Fig. 3. Steel production from virgin materials as share of total production for varying long-term demand growth (*x*-axis) and varying short-term demand growth (data series), modelled for the year 2050 (a) and 2100 (b).

(2010), who claims that the resource would last for approximately 135 years at a growth level of 3% from 2010 levels, and recycling of 80%. The study shows that the effect of recycling would be marginal for conserving the resource. However, Grosse's (2010) estimation is based on an average residence time of 7 years, which is significantly lower than the residence time assumed in this study (see Table 2).

In contrast, *Demand stagnation in 2050*, requires virgin material to the level that is available in the reserve (see Fig. 4b). Grosse (2010) also developed a similar scenario, assuming 3.5% demand growth rate until 2050 and then immediate stagnation. An effective recycling rate of 62% and a residence time of 17 years result in approximately 60% of the steel demand being covered by recycling after 2070. If the same demand growth assumptions are used in SAAM, the results show an increasing scrap availability compared to demand from 59% in 2070 to 76% in 2100. The reason behind the difference between Grosse (2010) and SAAM is that the recycling rates were assumed to increase over time in SAAM, while Grosse's analysis assumes a stable recycling rate at 62%. If the 62% recycling rate had been used in SAAM, the results would have shifted to 39% in 2070 and 48% scrap to meet demand in 2100. The longer residence times assumed in SAAM imply delay in achieving higher level of recycled material in the mix despite the reduced demand growth.

Several studies emphasize the importance of assumptions on residence times and sectoral split for the estimation of in-use stock as well as scrap availability (Grosse, 2010; Müller et al., 2011; Pauliuk et al., 2013). While Grosse (2010) estimated the average 17 years of residence time by relating it to the recycling rate, Pauliuk et al. (2013) estimated the residence time and the sectoral split using a model to minimize the difference between estimated scrap supply and historic demand of scrap. We claim that the approach of Grosse (2010) is too general, whereas the approach of Pauliuk et al. (2013) is not applicable since data is not available. In addition, Pauliuk et al.'s (2013) approach cannot be used for future predictions.

The residence time parameters were therefore assumed in line with the medium-term scenario for residence times by Müller et al. (2011). The sectoral split parameters were assumed to the average of the four historic examples presented in Pauliuk et al. (2013). The model developed by Pauliuk et al. 2013 showed that the choice of these parameters mimics the development of Canada and Japan quite closely. Nevertheless, the uncertainty of these parameters is high and has an influence on estimates for scrap availability (see Table 4). A regional representation would increase accuracy and should be considered in a future version of SAAM.

The results also showed that *Demand stagnation in 2100* would result in an in-use steel stock of 20 tonnes per capita in 2100 and almost 25 tonnes per capita in 2150. Those levels are much higher than the levels of currently industrialized economies, which lie somewhere between 8 and 16 tonnes per capita (shown as the coloured area in Fig. 5) (Müller et al., 2011; Pauliuk et al., 2013). If emerging and developing economies follow the same pattern as the industrialized economies, the global average of in-use steel stock should be significantly lower than 20–25 tonnes per capita at the level of stabilization. The *Demand stagnation in 2050* was created with this in mind and stabilizes at a level of 12 tonnes of in-use steel stock per capita, which is more in line with the levels indicated by studies of industrialized economies (Müller et al., 2011; Pauliuk et al., 2013).

Table 4
Sensitivity analysis of the impact of changes in residence times and sectoral split on scrap availability and in-use steel stock in 2050 according to SAAM.

	Scrap availability in 2050	Absolute in-use stock in 2050
Change of residence times		
5 years longer	−4%	+8%
10 years longer	−14%	+25%
5 years shorter	+8%	−15%
10 years shorter	+21%	−28%
Change of sectoral split		
Shift to long-term prod.	−12%	+29%
Shift to short-term prod.	+11%	−14%

4. Technology choices for steel production (ETSAP-TIAM)

Technology choices for future steel production were provided by ETSAP-TIAM. ETSAP-TIAM produced results for six scenarios. For each of the two demand scenarios, *Demand stagnation in 2100* and *Demand stagnation in 2050*, one reference scenario, one binding climate target scenario (i.e. the 3.5 RF scenario) and one binding climate target scenario without CCS availability (i.e. the 3.5 RF scenario (no CCS)) were produced. Section 4.1 highlights the cost-efficient technology pathways for future steel production, Section 4.2 discusses the influences on costs and prices while Section 4.3 discusses the relation between the CO_2 price and CCS deployment based on an ex-post calculation. Appendix A provides a complete graphical overview of the results.

4.1. Cost-efficient technology pathways

The results for the reference scenario showed that one of the cost-efficient technology pathways is based on COREX technology. This technology has the important advantage of producing large amounts of siderurgical gases that can be used in other sectors.

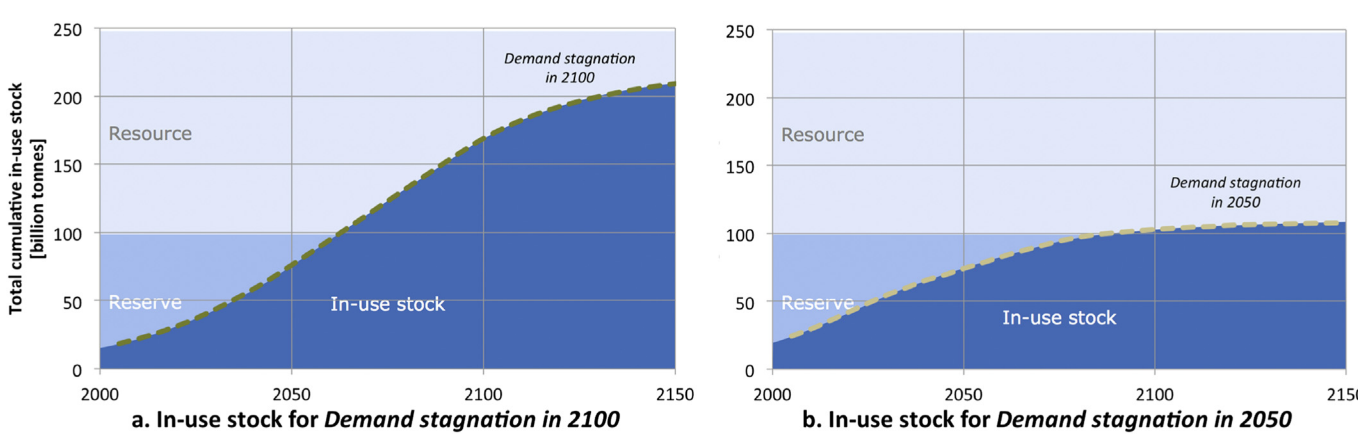

Fig. 4. Cumulative global in-use steel stock for two demand growth scenarios: *Demand stagnation in 2050* and *Demand stagnation in 2100*.

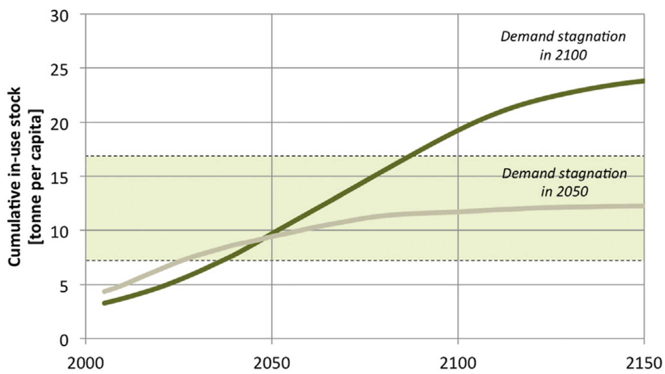

Fig. 5. Cumulative global in-use steel stock per capita for two demand growth scenarios: *Demand stagnation in 2050* and *Demand stagnation in 2100*.

However, at present, the European industry considers investment in the COREX technology unlikely. For that reason, Pardo and Moya (2013) excluded this technology option in their analysis. The results also showed that traditional blast furnaces enhanced with direct coal injection would be cost-efficient and in competition with the COREX technology.

Imposing a binding climate target can make iron production combined with CCS a cost-efficient technology for steel production (see Fig. 6 and Appendix A for further details). In this scenario, the main technologies competing for iron production are (i) the traditional blast furnace enhanced with top gas recycling and CCS, (ii) the traditional blast furnace enhanced with direct coal injection and CCS, and (iii) direct reduction to steel using hydrogen as reduction agent. Furthermore, the traditional blast furnace combining direct coal injection and CCS has the benefit of producing hydrogen as a by-product since the CO_2 removal is based on a shift reactor followed by a physical absorption of the CO_2 (Gielen, 2003). This technology is economically more attractive in this scenario due to the price increase of hydrogen. Hydrogen becomes an attractive resource due to its increased use in the transport sector (primarily aviation and heavy trucks) and in industry, under the imposed climate target.

In the scenario without CCS availability, direct reduction using hydrogen as reduction agent receives a more prominent position (see Fig. A1c and A1f in Appendix A). This production method is still energy intensive, although much less carbon intensive since the hydrogen can be produced using either electricity or biomass. It covers the total demand for steel to over 90% together with EAF production in 2100 (see Fig. A1c in Appendix A). The share of steel produced from iron is shifted towards classical blast furnaces (with and without top gas recycling) as well as classical blast furnaces using biomass for the reduction process.

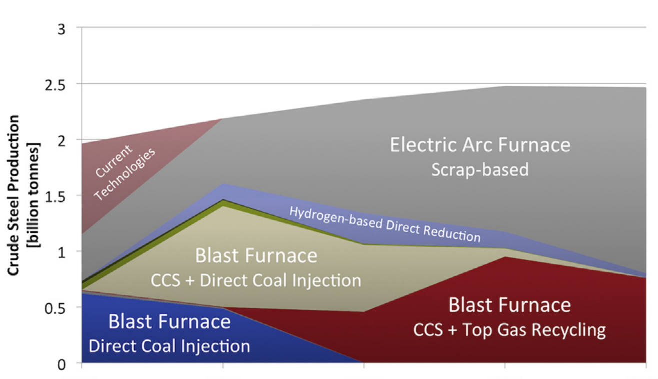

Fig. 6. Technology competition in the binding climate target scenario (3.5 RF scenario) for *Demand Stagnation in 2050*, based on ETSAP-TIAM results. Further details on technology choices are shown in Appendix A.

It is evident that steel production from virgin materials will still be needed in 2100 under both demand scenarios, confirming the results of SAAM (see SAAM results in Section 3.1). In absolute numbers, steel production from virgin materials will be significantly reduced under the *Demand stagnation in 2050* assumption. Nevertheless, the results showed that more than 50% of the total steel demand is met by steel production from virgin materials in 2050 in all scenarios (in some scenarios, significantly more than 50%).

Secondary steel production is a cost-efficient technology pathway in all scenarios. Furthermore, a binding climate target only slightly increases the share of EAF production in the total. The reason for this is that steel production from scrap is already cost-efficient in the reference scenario and does not need additional incentives for reaching its maximum capacity. Its expansion is actually limited by the availability of scrap. The difference between the two groups of demand scenarios is that, in the *Demand stagnation in 2100* scenario, society demands more steel initially (see Fig. A1 in Appendix A), which will be made available for secondary production at a later stage. As from 2050, scrap-based steel will be produced in amounts similar to today's primary steel, with a strong increase expected afterwards.

It should be noted that although EAFs are the major consumers of scrap, some scrap is also used in BOFs (as a fixed amount of supplementary feedstock to pig iron). This use of scrap is reduced in scenarios imposing a binding climate target, since the use of BOFs is lower in those scenarios (see Fig. A3 in Appendix A).

4.2. Influences on costs and prices (ETSAP-TIAM)

The demand evolution does not have a significant impact on the prices of scrap, iron and steel, except in the scenario without CCS availability. Without the pressure from the binding climate target in place, the prices are rather constant probably because of the assumption of constant mining costs of around 80 USD per tonne iron ore.

The current version of the model does not consider interregional trade of iron and steel products. However, to understand the scenarios' implications on trade, the regional crude steel prices as estimated by the model were analysed (see Fig. 7). Imposing a binding climate target shifts the crude steel price up, close to approximately 500 USD per tonne due to increased CO_2 and scrap costs. The exceptions are Australia, where the steel price is especially low, and China and South Korea, where the steel price is slightly higher. In the scenario without CCS availability, the differences in crude steel price between regions became more pronounced. China, India, Japan, Middle East, South Korea, USA and Western Europe all have crude steel prices above 1000 USD per tonne in *Demand stagnation in 2100* scenario. In these countries, the price of electricity increases with a factor 2.5, compared to the reference scenario, due to the increased CO_2 price (see Fig. 8), thus making electricity production expensive. Regional conditions, such as scarcity of coal, also have a significant impact on steel prices.

The CO_2 price is not significantly influenced by steel demand trends, whereas the CCS availability has a significant impact (see comparison in Fig. 8). The CO_2 price triples in 2100 if CCS is not available. This increase is related to the model being forced to use technologies that emit CO_2 when other alternatives are not available for low-carbon electricity or steel production. This condition opens the possibility to introduce renewable technologies that would otherwise not be considered cost-efficient in a scenario with CCS, especially in the electricity sector. Since electricity use in the steel sector is limited by scrap availability rather than the electricity

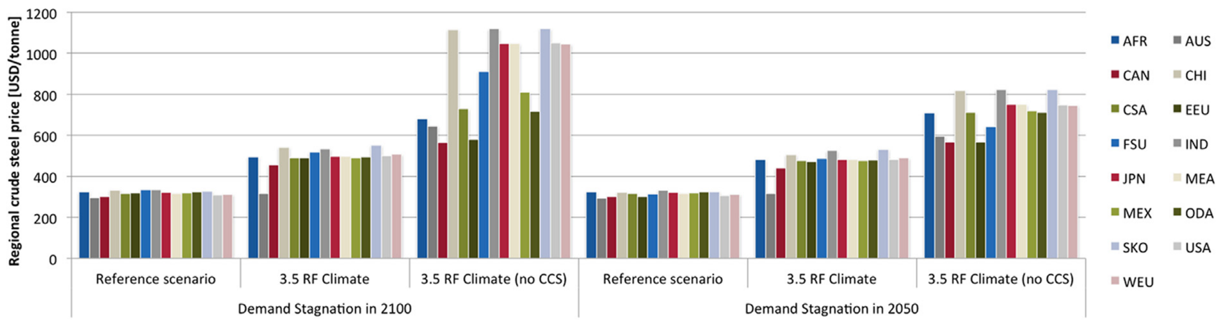

Fig. 7. Regional crude steel price for the different scenarios in the year 2060.

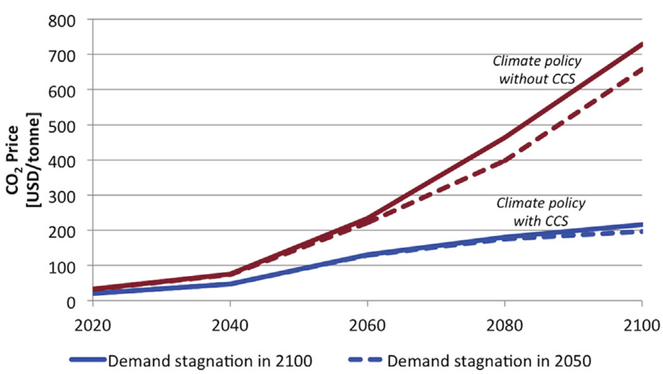

Fig. 8. CO_2 price for the scenarios with a binding climate target.

price, the results of the binding climate target scenario without CCS availability provide robust indications for iron and steel production technology choices. However, the societal results from this scenario (e.g. the CO_2 price) should be used with caution. Inclusion of additional renewable energy production technologies, which are not currently part of the renewable potential of ETSAP-TIAM, may help alleviate this issue.

A decomposition of the price for 1 tonne of crude steel showed that the price for direct CO_2 emissions is the only cost related to energy use when a binding climate target is imposed. In this case, the energy cost is covered by the income from selling produced gases (mostly hydrogen). If CCS is not an option, blast furnace using biomass is the most cost-efficient technology. In this case, the energy cost is significantly higher due to biomass resource competition, while the cost for direct CO_2 emissions is low (see Fig. 9). It should be mentioned that the total price of steel is equal in both production routes from the model's perspective, since no distinction is made for steel quality. Hence, the model considers the steel from the two routes to be traded in the same market.

The major component of the steel price in the secondary route is the scrap, which is approximately between two thirds and three fourths of the total price, depending on the scenario. In this case, the price of scrap is inflated due to scarcity of the commodity worldwide. The price of scrap includes a scarcity value resulting also in the need to go for more CO_2 emission intensive alternatives when scrap availability is limited. The CO_2 emission intensive alternatives are especially expensive in the scenario without CCS availability, which is reflected in the CO_2 price (see Fig. 8). The inflation of the scrap price with the scarcity value means that there is room for additional costs in the recycling and recovery of scrap without affecting the ETSAP-TIAM results. Based on this, it is plausible that the recycling rate would be significantly higher closer to the end of the century, confirming the assumption of approaching 90% recycling in 2100. The situation of scarcity driving up prices has already been observed in the case of copper, though in this case there is scarcity in virgin material as well as recycled (Conrad, 1999).

Under all scenarios, the future scrap market will have significant value. However, under a binding climate target and no CCS availability, the price of scrap almost triples compared to the reference, indicating harsh competition among scrap users.

4.3. Impact of CO_2 price on CCS deployment (ETSAP-TIAM and ex-post calculation)

Imposing a binding climate target makes iron production using CCS cost-efficient. Both the traditional blast furnace with CCS and the blast furnace with top gas recycling and CCS are preferable to any non-CCS option (see the results for the 3.5 RF scenario in Fig. A2b and A2e in Appendix A). An additional analysis was performed to investigate what climate change mitigation ambition is needed to achieve a cost-efficient implementation of CCS in raw iron production. The CO_2 price is a meaningful indicator that reflects the society's climate change mitigation ambition.

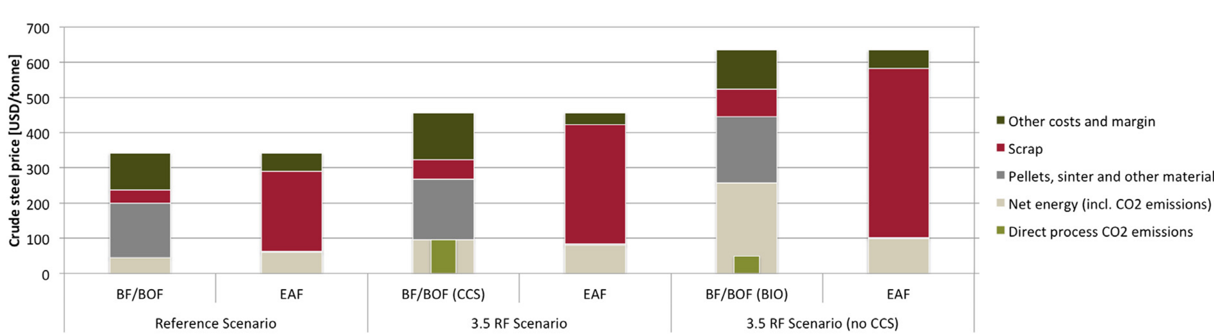

Fig. 9. Decomposition of price of one tonne of crude steel (Western Europe, 2060, *Demand stagnation in 2050*). The cost of direct CO_2 emissions are included in the net energy cost, but also given explicitly (the narrow bars).

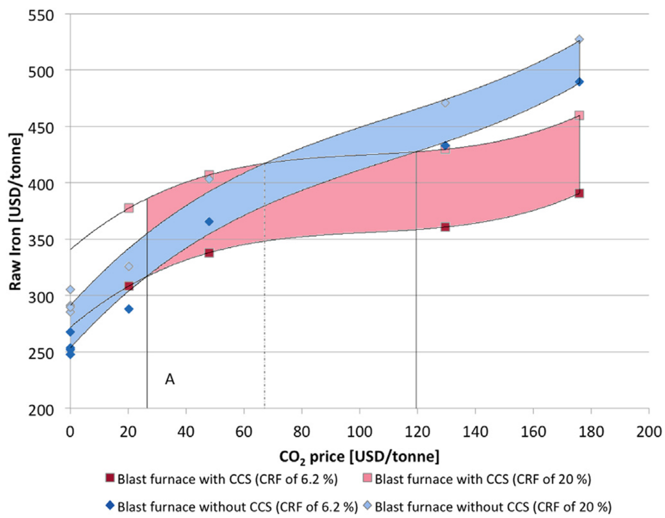

Fig. 10. The price development of raw iron as a function of the CO_2 price for the blast furnace process with and without CCS for different capital recovery factors (CRFs).

We analyse the impact of the CO_2 price on the cost of producing raw iron for the traditional blast furnace with and without CCS. An increasing CO_2 price affects the costs of both processes strongly as it penalises the net CO_2 emissions and also alters the prices of commodities such as sinter, electricity and hydrogen. From the ETSAP-TIAM results for Western Europe, the CO_2 price and the iron price is taken for the periods 2020, 2040, 2060 and 2080. For the non-competitive technologies (blast furnace without CCS in the 3.5 RF scenario and blast furnace with CCS in the reference scenario), the iron price is calculated ex-post using the same commodity prices. The result is plotted in the two lower trend lines in Fig. 10.The blast furnace without CCS shows a much higher sensitivity to the changing CO_2 price.

In ETSAP-TIAM, the capital recovery factor[1] (CRF) for technology investments is rather low (6.2%) as the investment is annualised using a discount rate of 5% and the technical lifetime of 30 years. To reflect the reality of a business model for which higher discount rates or shorter economic lifetime are desirable (as for the case of manufacturing industries), the same relation between CO_2 price and raw iron price was calculated with a CRF of 20% (see the two upper trend lines in Fig. 10).

The blast furnace with CCS becomes cost-efficient as from approx. 25 USD per tonne of CO_2, if a CRF of 6.2% is assumed for both technologies. If the CRF is increased to 20% for both technologies, the blast furnace with CCS becomes cost-efficient at approx. 70 USD per tonne of CO_2. However, due to the higher risks of investing in innovative CCS-based technology, it is likely that a higher CRF is used for the CCS-based technology. In the extreme case, one would use CRF of 20% for the CCS-based technology and 6.2% for the alternative. In this case, CO_2 prices ranging from 25 to 120 USD per tonne are necessary for steel production using CCS to be a cost-efficient technology pathway.

5. Conclusions and policy implications

The objective of this study was to analyse how global climate targets may influence future steel production technology choices in the context of global long-term steel use. Scenarios were created to investigate the impact of future steel demand patterns, a binding climate target and no availability of CCS as a technology option.

Despite the theoretically high recycling rate of 90% for steel, significant steel production from virgin materials is required for a long time in the future. At the global level, steel production from virgin materials will need to be at least 50% in 2050 to meet demand under the assumption of unchanged steel applications and corresponding lifetimes. Even if the growth of steel demand is drastically reduced, steel production from virgin materials will be needed due to the time lag of steel accumulation in society.

The results showed that significant energy efficiency improvements of current steel production processes, such as top gas recycling, can only meet the binding climate target if combined with CCS. Higher CO_2 reductions can be attained by new processes, which are intrinsically more energy efficient and/or low in CO_2 emissions. Reduction agents, such as hydrogen and biomass, can also significantly reduce the CO_2 emissions. Since hydrogen can be produced from energy sources such as biomass and electricity, the technology can also be virtually CO_2 emission neutral. It is interesting to note that the steel sector could be a very large consumer of electricity by using hydrogen as a reduction agent. Such technology pathways become cost-efficient at higher CO_2 prices, especially in a scenario without CCS availability. The results also showed that high climate ambition only has a minor impact on the use of scrap.

The results of this study are useful for understanding the implications of global climate policy design. Although unlikely in the short- and medium-term (Finus et al., 2013), global climate policies may be agreed upon over the time period analysed in this study. The results showed that targeting a limitation of the global mean temperature increase in the range of 2.4–3.2 °C would result in drastic increases of the CO_2 price during the coming century. A decomposition of the crude steel price revealed that the price would be inflated due to the increased CO_2 and scrap prices. The scrap price will increase due to the future scarcity of the resource, since production from scrap would be favourable from an emissions point of view.

A binding climate target tend to induce a regional differentiation of prices, indicating that regions such as China, India and South Korea may have difficulties meeting their domestic demand due to the high CO_2 price and their dependence on fossil fuels for energy production. Today these countries are among the low-cost countries for steel production (Okereke and McDaniels, 2012), but the results suggest that a shift in global trade patterns of steel products may occur. A more detailed analysis of the trade of steel commodities for the cost-efficient technology pathways presented in this study may highlight the implications for climate policy as well as trade policy design in different regions.

Acknowledgement

The authors would like to thank Ernesto Ubieto Udina at JRC of the European Commission, as well as the three anonymous reviewers for their comments on the paper. A first version of this paper was presented at the ESA2 Workshop – Shaping our energy system – combining European modelling expertise – held in Brussels, 24 January 2013, and the International Energy Workshop held in Paris, 19–21 June 2013. The authors thank the conference participants for valuable comments at those occasions.

This paper was developed within the scope of Energy Systems Analysis Agency (ESA^2). ESA^2 is an independent consortium of renowned universities and research institutions from five European countries providing qualified decision support for public and private clients in areas related to energy and environmental policy. ESA^2 originated from KIC InnoEnergy at the European Institute of Innovation and Technology (EIT). More information is available at www.esa2.eu.

[1] A capital recovery factor is the ratio of a constant annuity to the present value of receiving that annuity for a given length of time. Using a 5% interest rate over a 30 years' period, the capital recovery factor is 6.2%. Using a 5% interest over a 5.5 years' period or 15% interest over a 7.5 years' period result in a capital recovery factor of 20%.

Appendix A

List of regions

AFR	Africa
AUS	Australia and New Zealand
CAN	Canada
CHI	China
CSA	Central and South America
EEU	Eastern Europe
FSU	Former Soviet Union
IND	India
JPN	Japan
MEA	Middle East
MEX	Mexico
ODA	Developing Asia
SKO	South Korea
USA	United States
WEU	Western Europe

Details on the countries included in each region is available in Loulou and Labriet (2007b).

ETSAP-TIAM Results in Appendix A

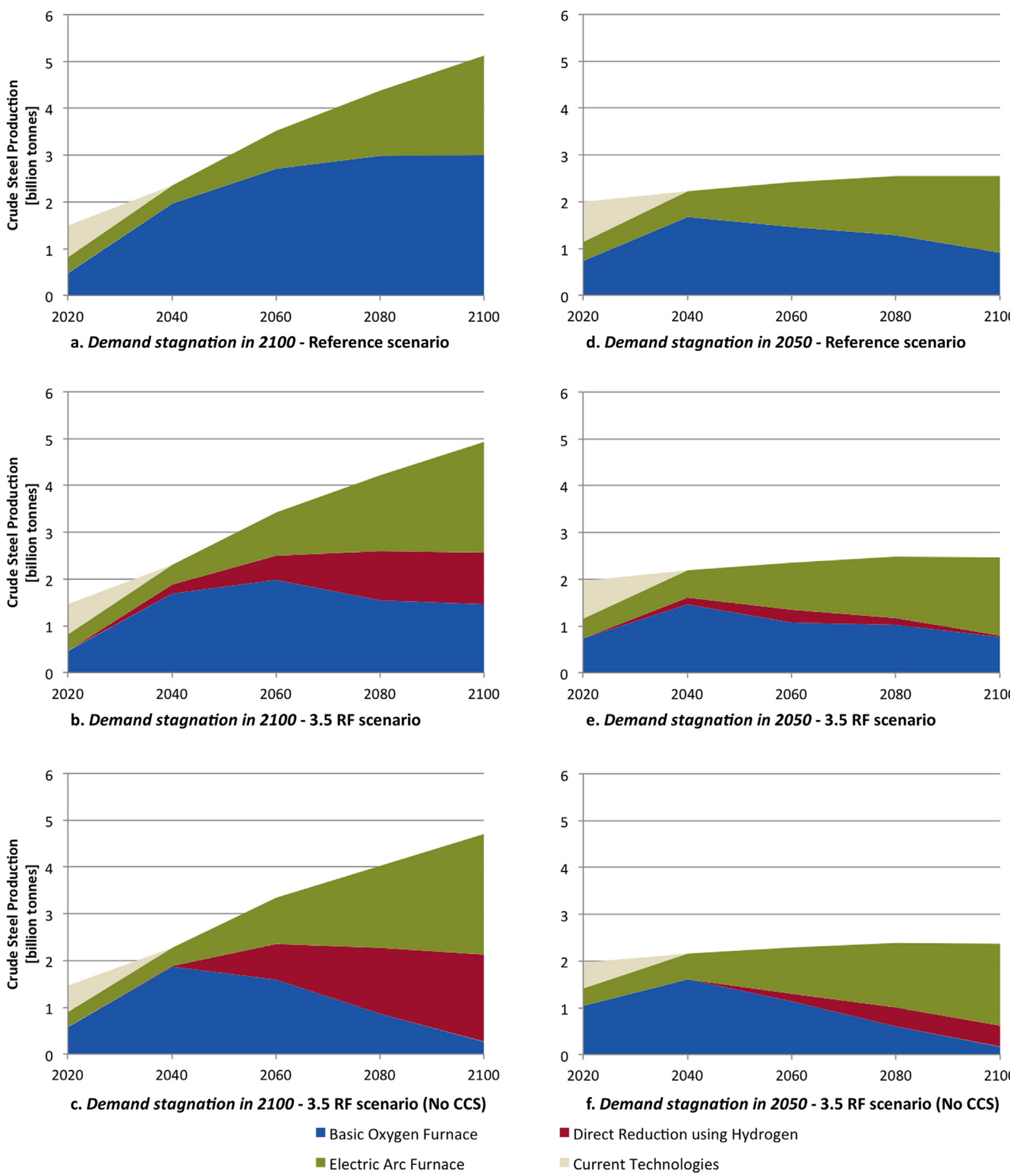

Fig. A1. Future global steel production by technology group.

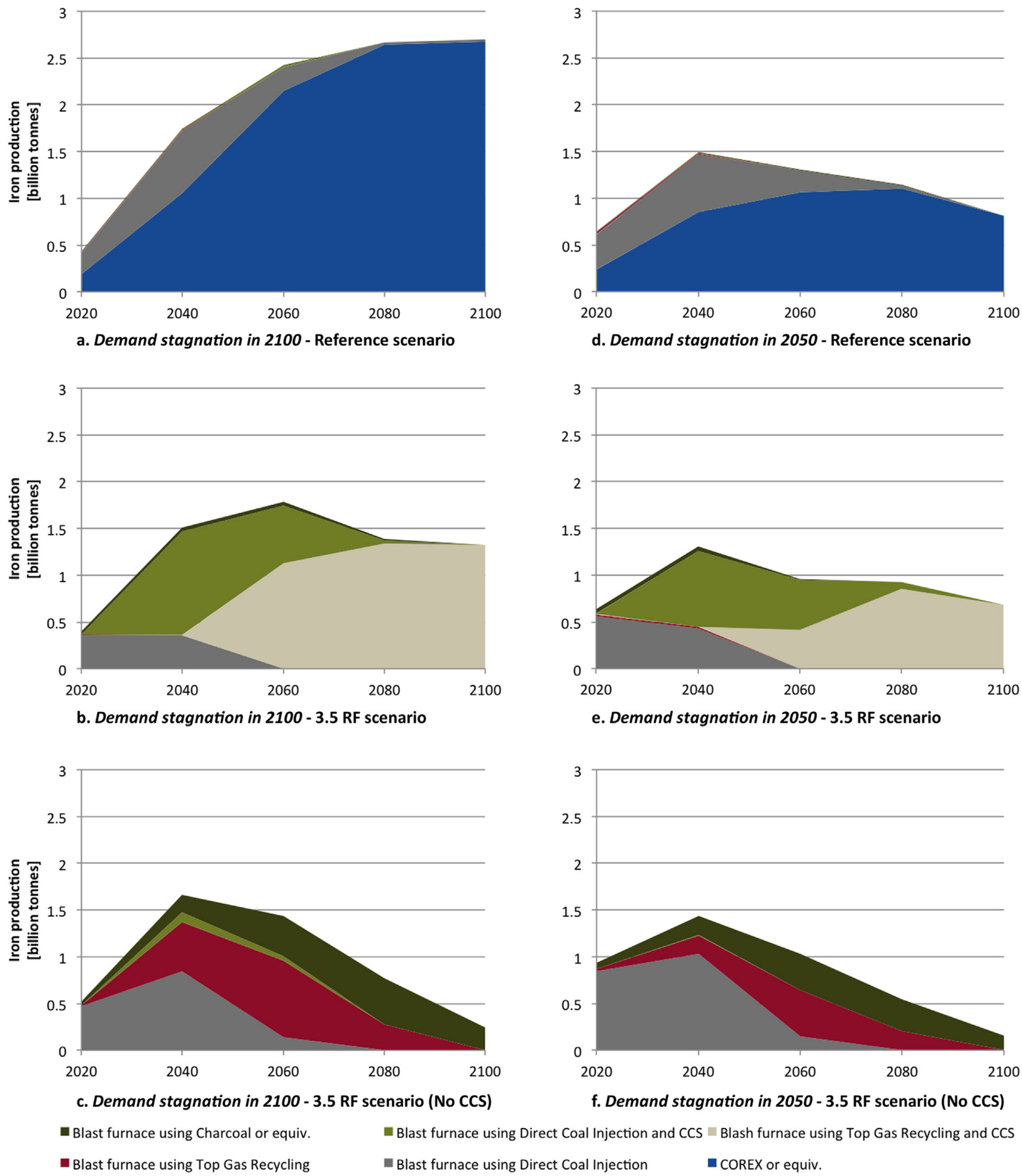

Fig. A2. Future global iron production by technology group.

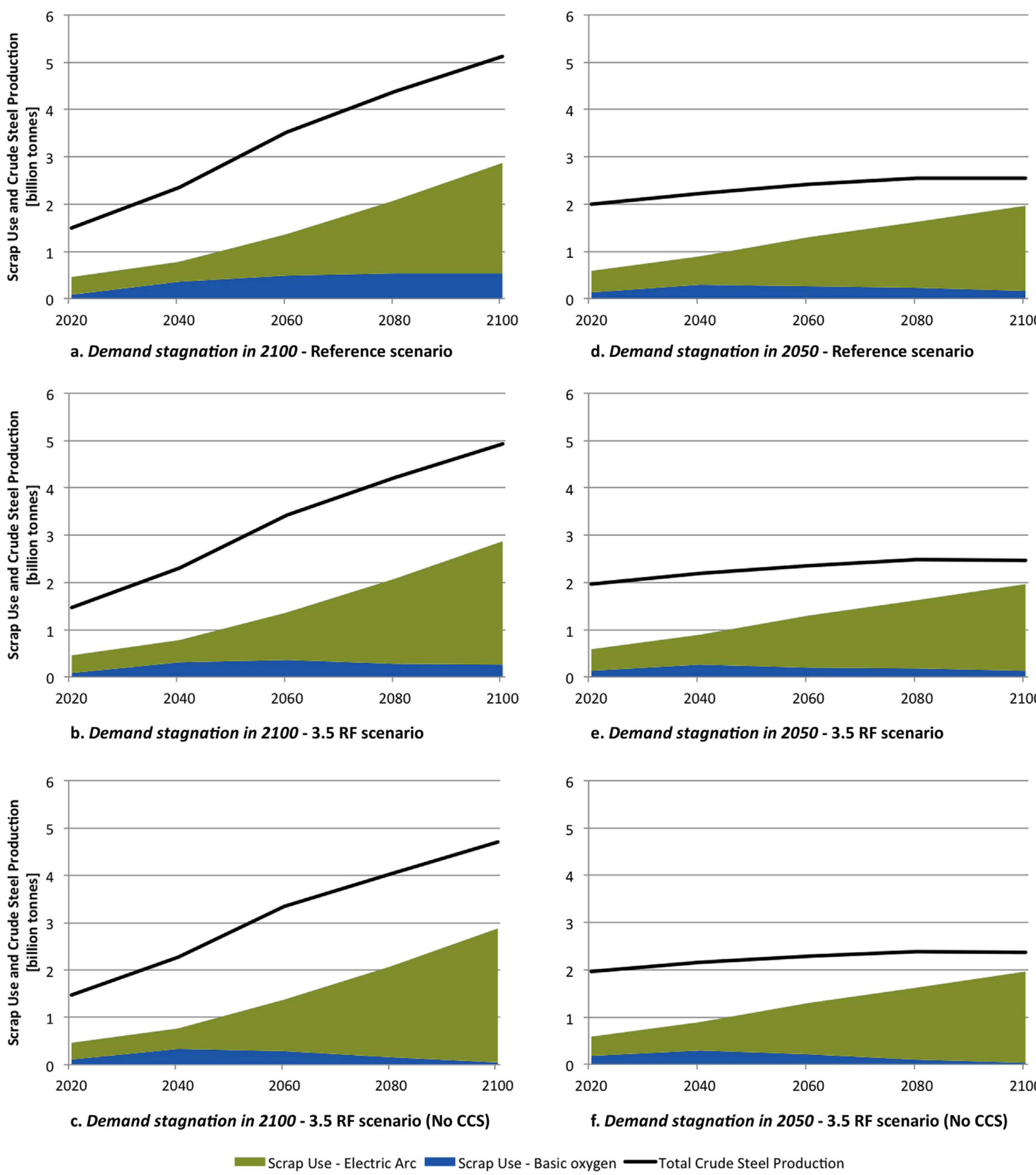

Fig. A3. Scrap use compared to total crude steel production.

Appendix B

Table B1
Technology detail implemented in ETSAP-TIAM for steel production.

Attribute	Process/Commodity	Pellet production	Sinter production	Sinter production (BIO)	Oxygen production	Blast furnace using charcoal or equiv.	Blast furnace using direct coal injection	Blast furnace using direct coal injection and CCS	Blast furnace using top gas recycling	Blast furnace using top gas recycling and CCS	Basic oxygen furnace	COREX	COREX using CCS	Electric arc furnace	Electric arc furnace with DRI	Direct reduction	Direct reduction using CCS	Direct reduction using hydrogen (incl. Refinement and finishing)	Cast iron Cupola	Cyclone Convertor furnace CCF	Ferro Chrome Smelting furnace	Finishing processes
INPUT	Hard Coal [PJ]						6.2	6.2	5.2	5.2		27.0	27.0							20.1		
	Coke [PJ]	1.0	1.2				9.3	9.3	5.9	5.9		3.1	3.1								15.4	
	Electricity [PJ]	1.1	0.1	0.1	0.7	0.5	1.1	1.1	0.2	0.3	0.1	0.3	1.1	2.0	2.3	0.7	0.8	0.7	4.6	1.3	11.3	3.0
	Natural Gas [PJ]													0.5		11.0	11.2		11.4			0.5
	Heavy Fuel Oil [PJ]																				0.8	
	Blast Furnace Gas [PJ]																			2.0	0.6	
	High Temperature Heat [PJ]																				0.9	0.1
	Biomass [PJ]			1.5		18.0																
	Hydrogen Synthetic Gas [PJ]																	17.0				
	Lump ore [Mton]	1.0	1.0	1.0								0.8	0.8					1.5			2.3	
	Pellet [Mton]					0.2	0.2	0.2				0.8	0.8			1.5	1.5					
	Sinter [Mton]					1.3	1.3	1.3	1.5	1.5										1.5		
	Crude Steel [Mton]																					1.0
	Oxygen [Mton]					0.1	0.1	0.1	0.5	0.5	0.1	0.7	0.7	0.1	0.5					0.7		
	DRI Iron [Mton]														1.1							
	Quick Lime [Mton]										0.1											
	Raw Iron [Mton]										0.9											
	Scrap Iron [Mton]										0.2			1.1					1.3			
OUTPUT	Blast-Furnace Gas [PJ]					3.3	3.3													4.0	8.1	
	BF Gas TGR no CCS [PJ]								0.7													
	BF Gas Purified [PJ]									0.7												
	Corex Gas [PJ]											10.9										
	Corex Gas Purified [PJ]																					
	Hydrogen Synthetic Gas [PJ]							3.0														
	Basic Oxygen Furnace Gas [PJ]										0.7											
	High Temperature Heat [PJ]																			4.3		
	Pellet [Mton]	1.0																				
	Sinter [Mton]		1.0	1.0																		
	Raw Iron [Mton]					1.0	1.0	1.0	1.0	1.0		1.0	1.0							1.0		
	Blast Furnace Slag [Mton]					0.3	0.3	0.3	0.3	0.3		0.4	0.4							0.3	1.2	
	Iron and Steel Demand [Mton]																	1.0				1.0
	Crude Steel [Mton]										1.0			1.0	1.0				1.0			
	DRI Iron [Mton]															1.0	1.0					
	Ferrochrome [Mton]																				1.0	
	Oxygen [Mton]				1.0																	
	Sinked CO_2 from IND [kton]							746		796			763				427					
Availability [%]		95%	95%	95%	85%	85%	85%	85%	85%	85%	85%	85%	85%	90%	90%	85%	85%	85%	90%	85%	90%	90%
Lifetime [years]		25	25	25	30	30	30	30	30	30	30	25	25	25	20	30	30	40	30	25	30	20
Investment cost [€2010/Mt/year]		62	56	70	200	382	273	500	387	500	113	373	600	169	113	100	115	400	1126	225	768	225
Variable O&M costs [€2010/Mt]		4.8	6.2	6.2		2.0	2.0	5.0	3.5	5.0	56.3	2.3	5.0	21.4	28.2	1.2	2.0	2.0	225.2	5.6	81.9	11.3
Fixed O&M costs [€2010/Mt]		3.4	2.8	2.8	10.0	10.0	10.0	15.0	12.5	15.0	4.5	10.0	15.0	13.5	4.5	2.0	2.0	10.0	112.6	11.3	140.7	56.3
Start year		2006	2006	2020	2006	2005	2005	2020	2010	2020	2006	2006	2020	2006	2006	2001	2010	2030	2006	2006	2006	2006

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